A case study in the local estimation of shear-wave logs

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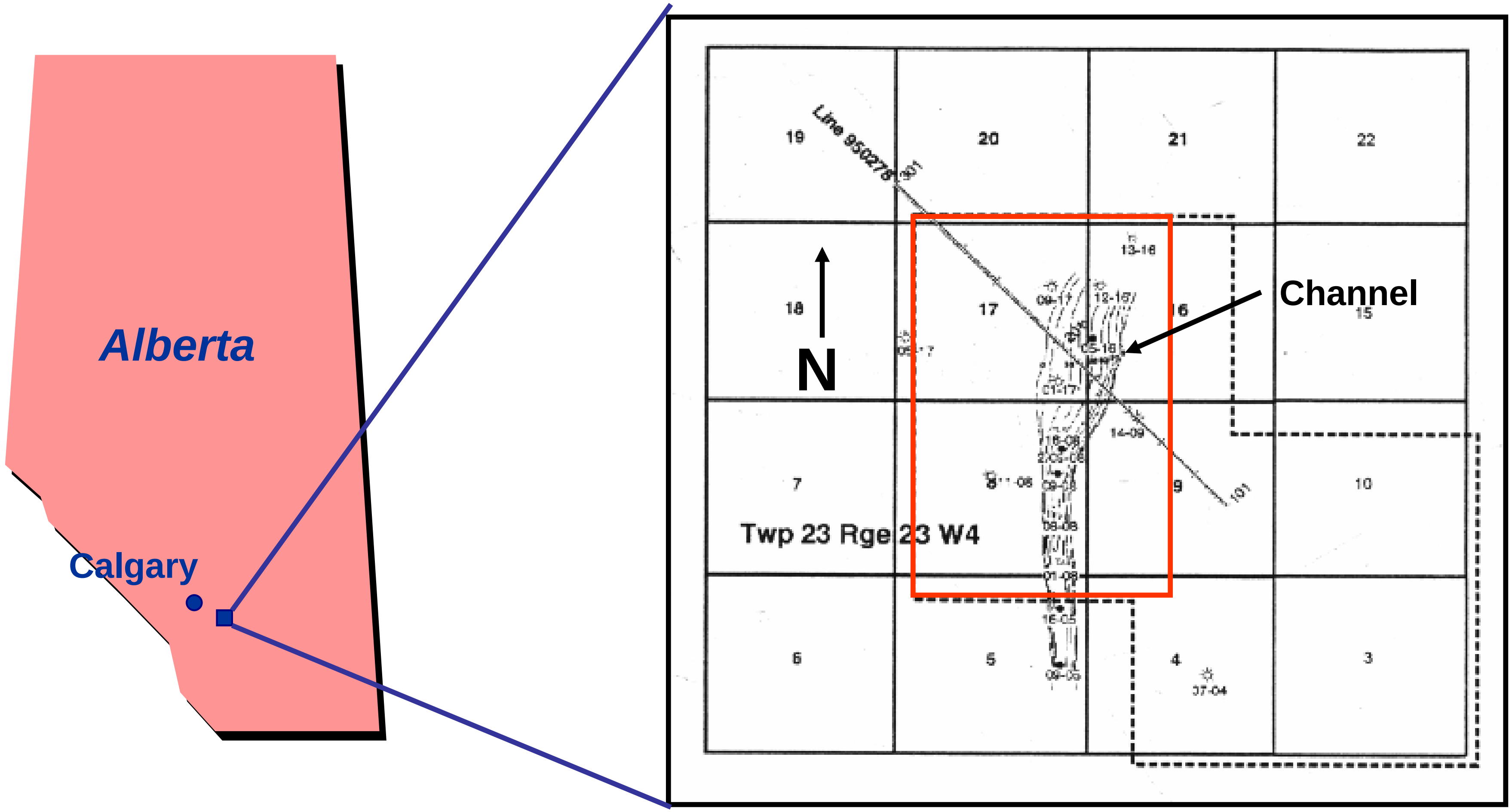
Introduction

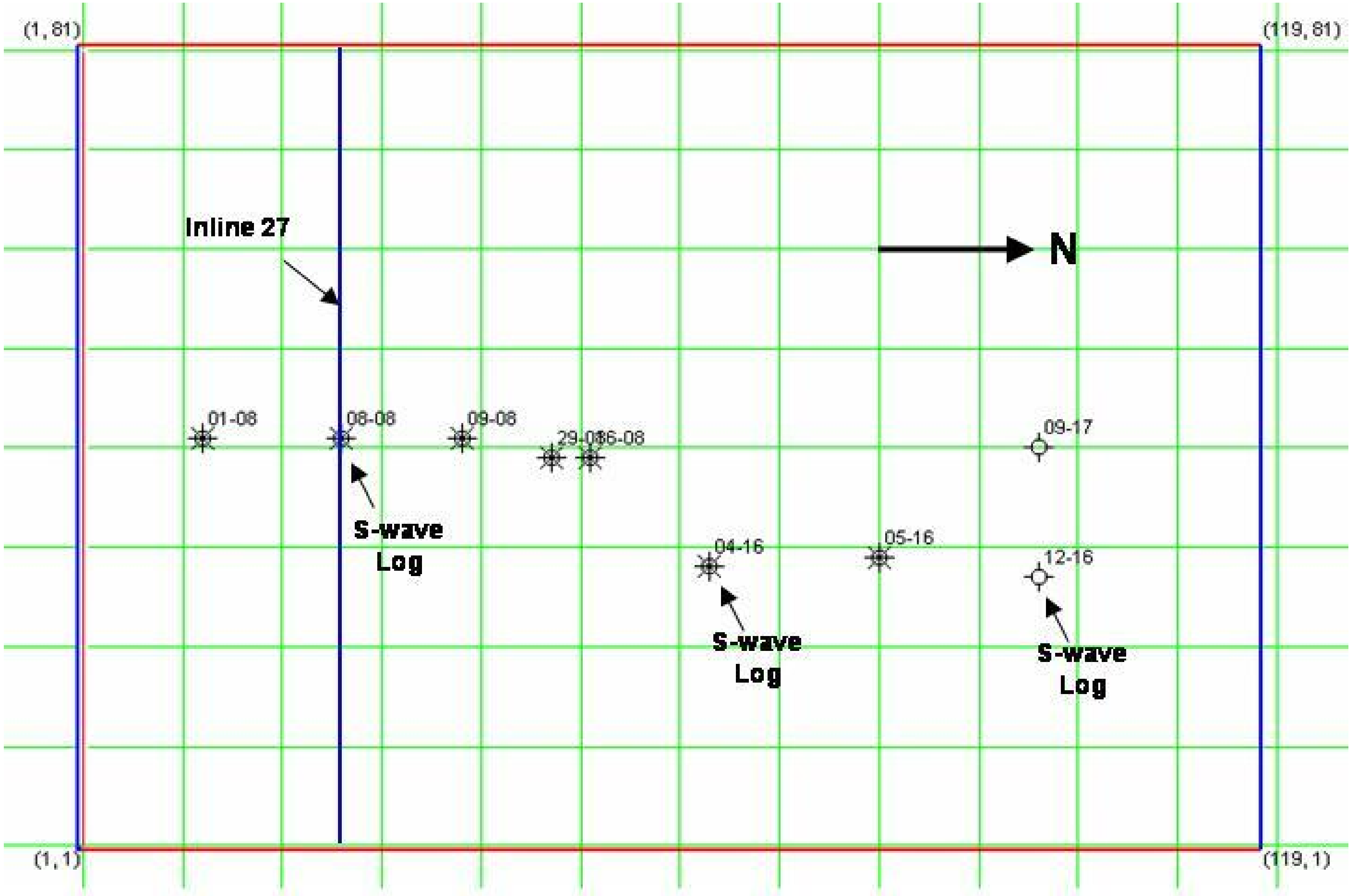
- The traditional approach to creating pseudo-S-wave velocity logs involves applying a linear regression equation to a P-wave velocity log.
- In this talk, we will use a multilinear transform to predict S-wave velocity logs from combinations of other logs.
- This will result in the derivation of a new relationship for the prediction of S-wave velocity logs.
- This relationship will be used to create new S-wave velocity logs which in turn will be used to predict S-wave impedance from seismic data.

The Blackfoot survey



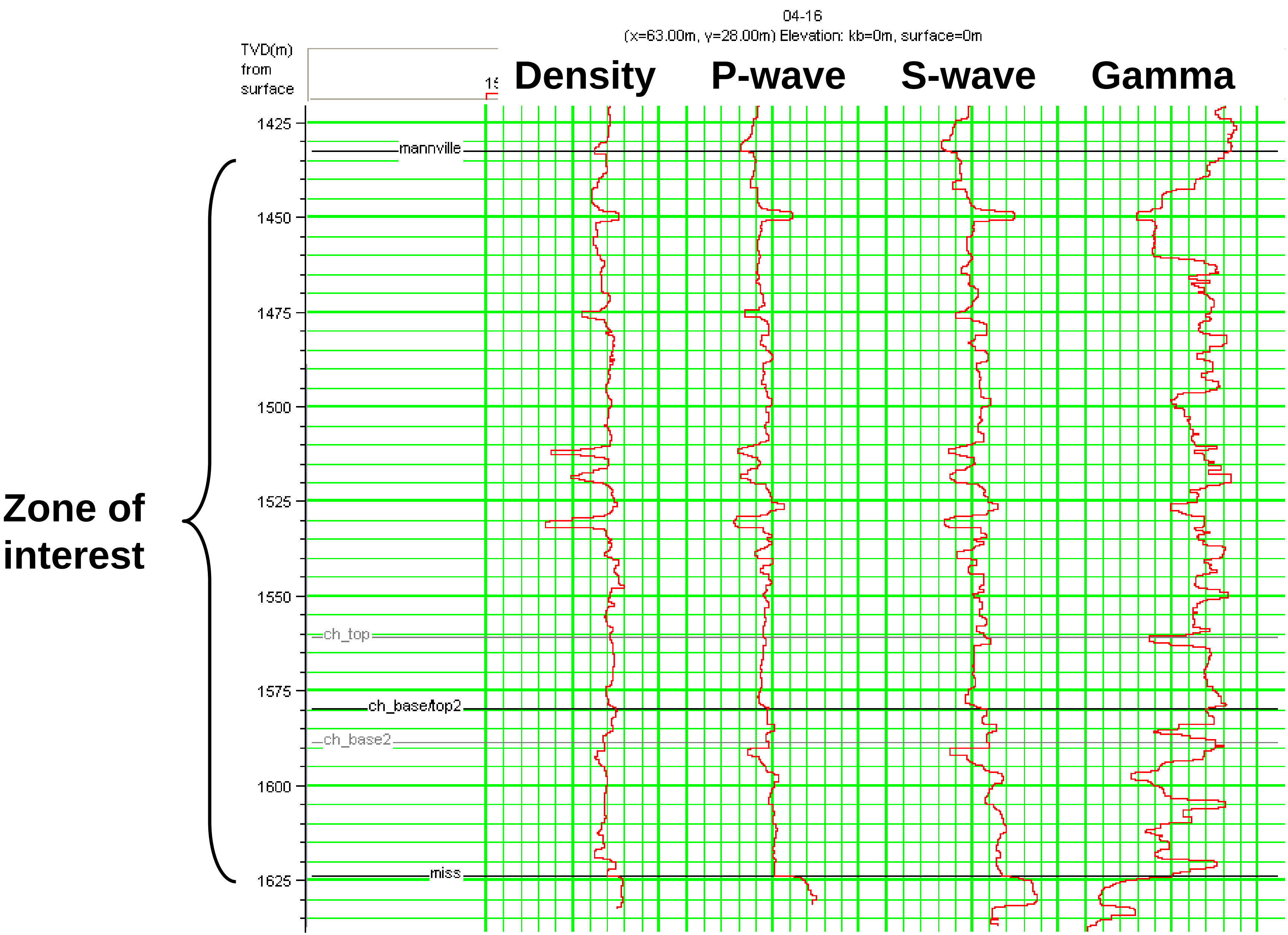
This map shows the location of the Blackfoot survey area, with the portion used in this study outlined in red. The objective, a Glauconitic channel within the Lower Cretaceous Mannville formation, is shown running north-south on the map. The survey was recorded in October, 1995 for PanCanadian Petroleum.

Base Map



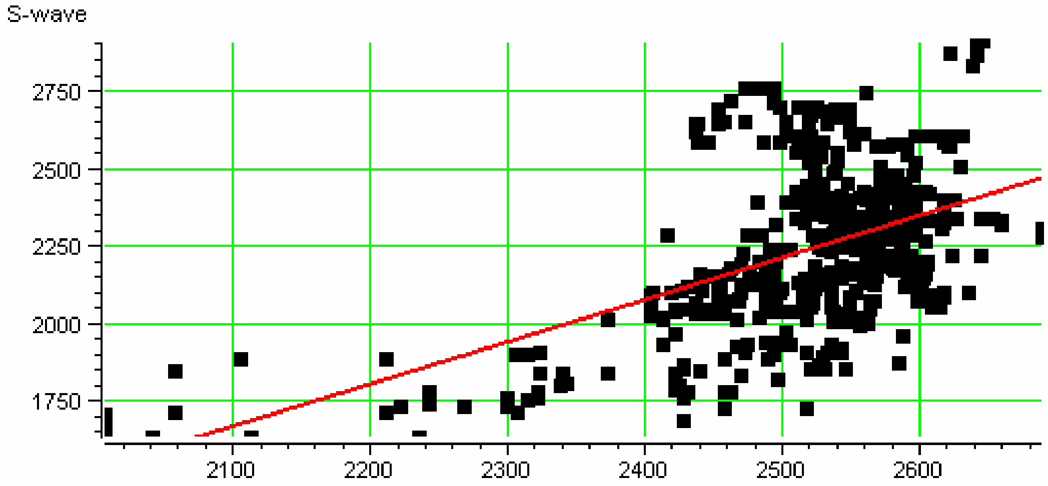
This base map showing nine wells in the area, of which only the ones marked with an arrow contain S-wave velocity logs.

Well 04-16

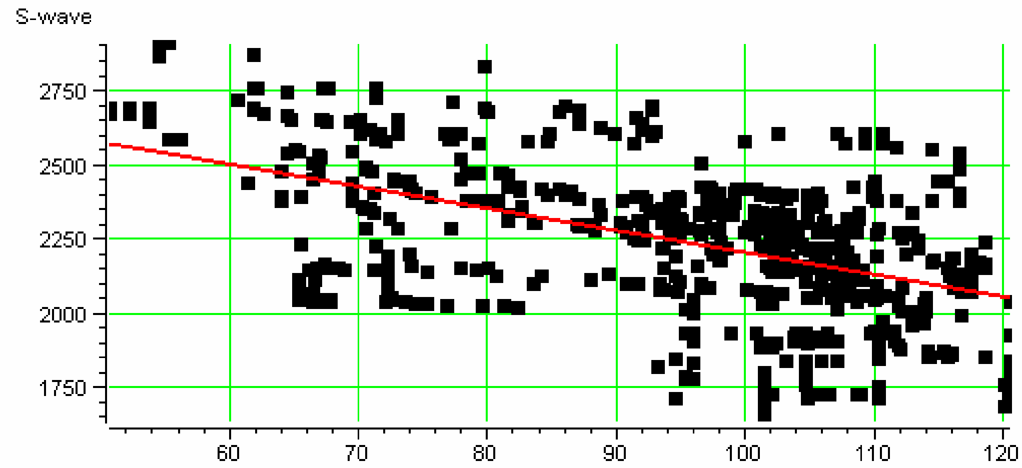


Well 04-16, displaying density, P-wave velocity, S-wave velocity and gamma ray logs.

04-16 Crossplots

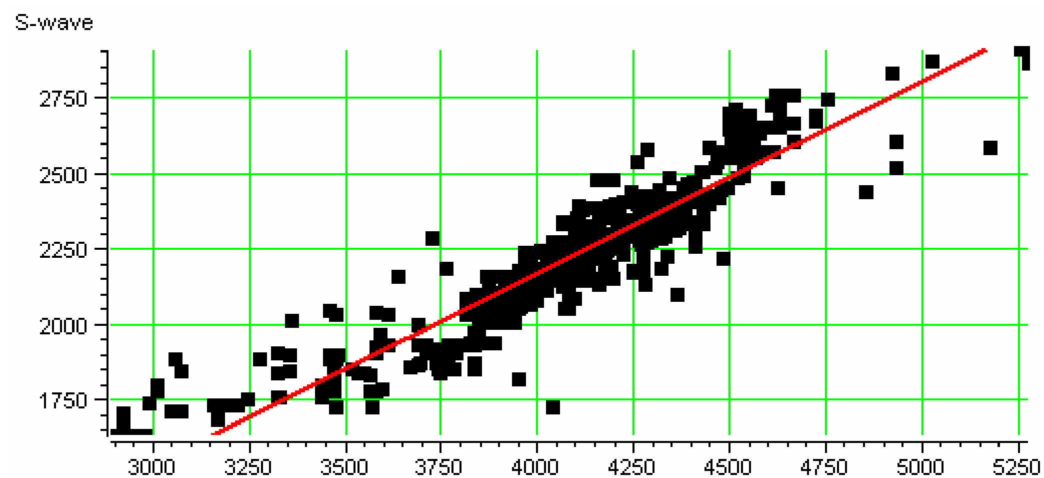


(a) Density



(b) Gamma Ray

Crossplots from well 04-16 of S-wave velocity versus (a) density, (b) gamma ray, (c) P-wave velocity. Note excellent correlation between P and S-wave velocity logs.



(c) P-wave

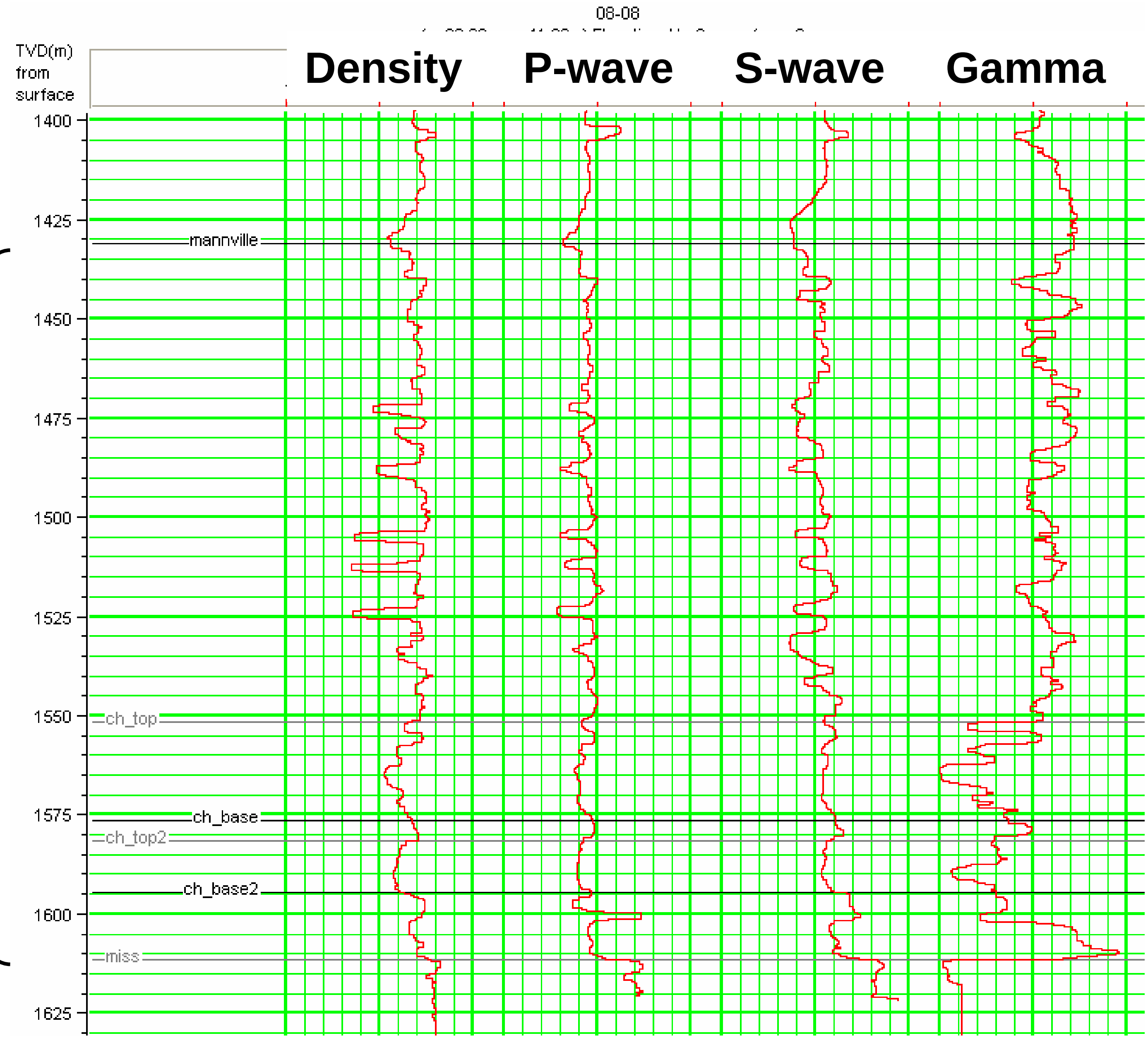
04-16 Regression Statistics

S-wave velocity versus:	P-wave velocity	Density	Gamma Ray
Intercept (*a*)	-366.95	-1182.76	2948.41
Slope (*b*)	0.634	1.357	-7.434
Correlation Coeff.	0.9305	0.5030	-0.4845
RMS Error	92.251	217.683	220.329

Regression statistics for the crossplots of the well logs in well 04-16.

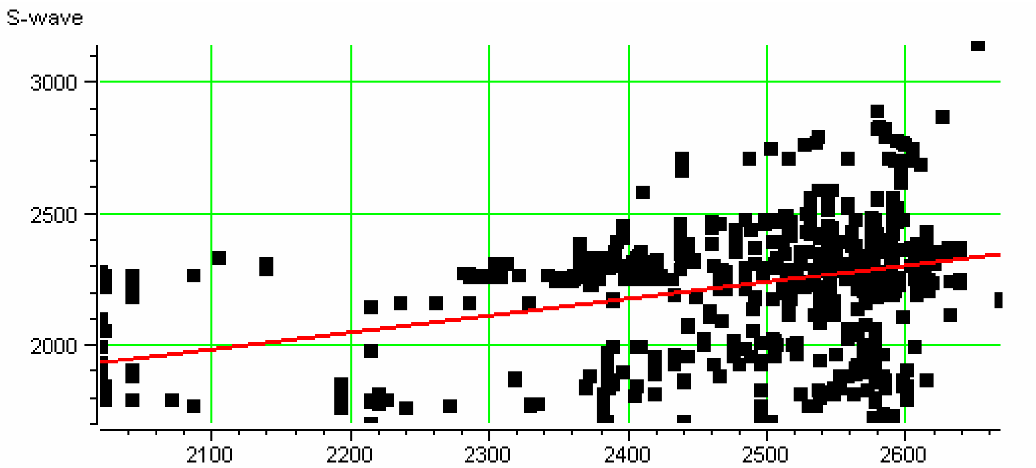
Well 08-08

Zone of interest

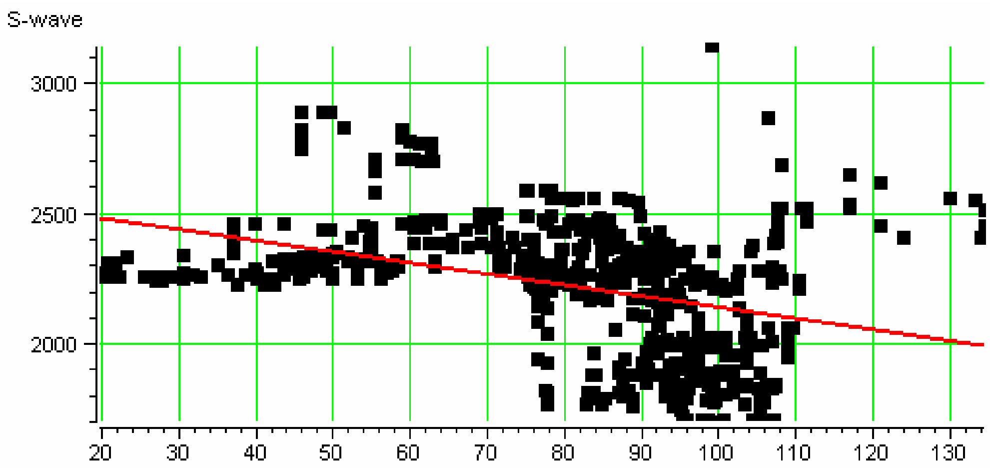


Well 08-08, displaying density, P-wave velocity, S-wave velocity and gamma ray logs.

08-08 Crossplots

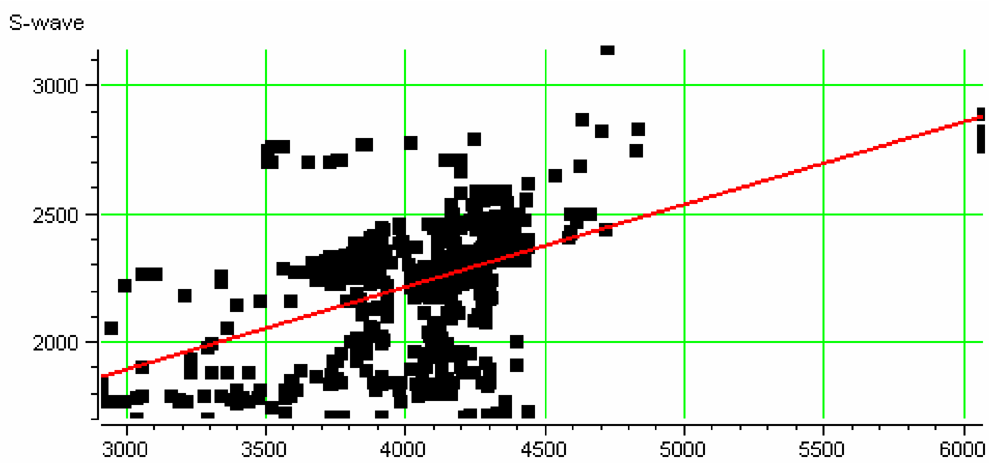


(a) Density



(b) Gamma Ray

Crossplots from well 08-08 of S-wave velocity versus (a) density, (b) gamma ray, (c) P-wave velocity. Note poor correlation between P and S-wave velocity logs.



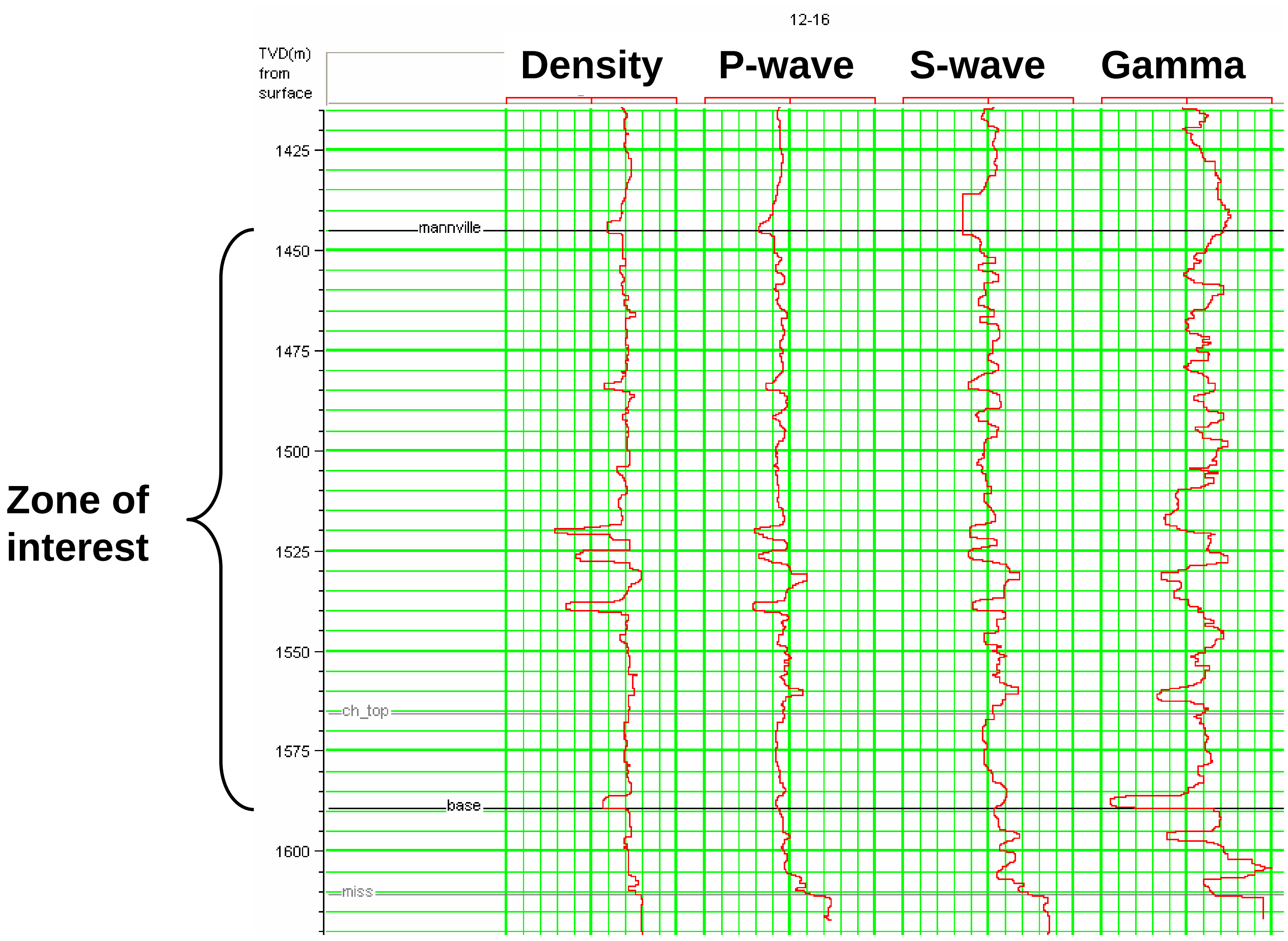
(c) P-wave

08-08 Regression Statistics

S-wave velocity versus:	P-wave velocity	Density	Gamma Ray
Intercept (*a*)	182.507	-482.073	2541.01
Slope (*b*)	0.496	1.070	-3.586
Correlation Coeff.	0.7766	0.5376	-0.2460
RMS Error	140.992	188.716	216.921

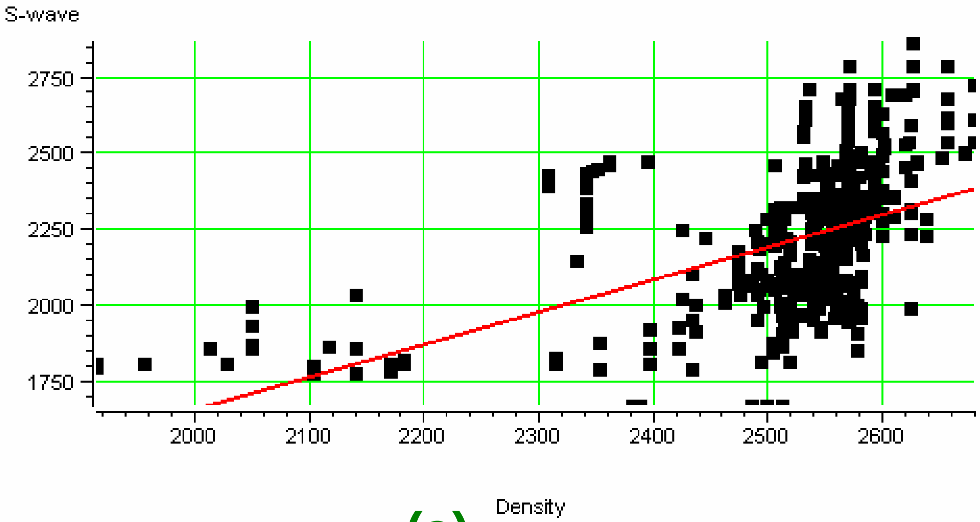
Regression statistics for the crossplots of the well logs in well 08-08.

Well 12-16

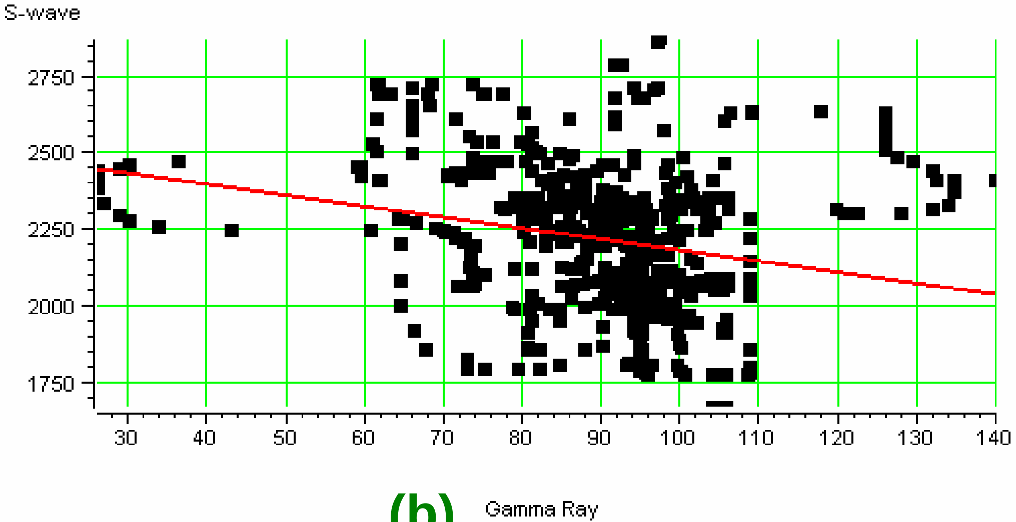


Well 12-16, displaying density, P-wave velocity, S-wave velocity and gamma ray logs.

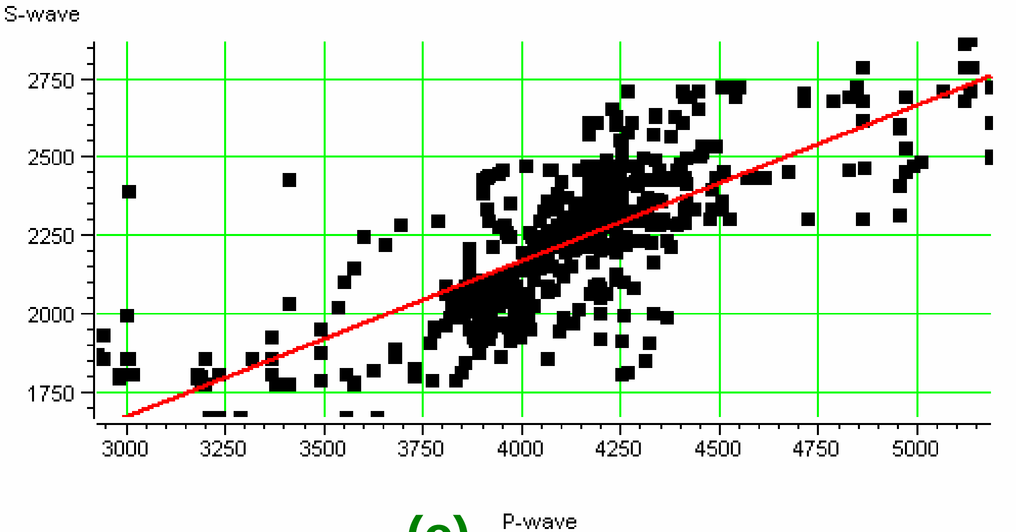
12-16 Crossplots



(a)



(b)



(c)

Crossplots from well 12-16 of S-wave velocity versus (a) density, (b) gamma ray, (c) P-wave velocity. Note again a poor correlation between P and S-wave velocity logs.

12-16 Regression Statistics

S-wave velocity versus:	P-wave velocity	Density	Gamma Ray
Intercept (*a*)	932.143	661.755	2567.9
Slope (*b*)	0.321	0.631	-4.254
Correlation Coeff.	0.4901	0.3283	-0.3864
RMS Error	214.734	232.702	227.22

Regression statistics for the crossplots of the well logs in well 12-16.

Statistics for all three wells

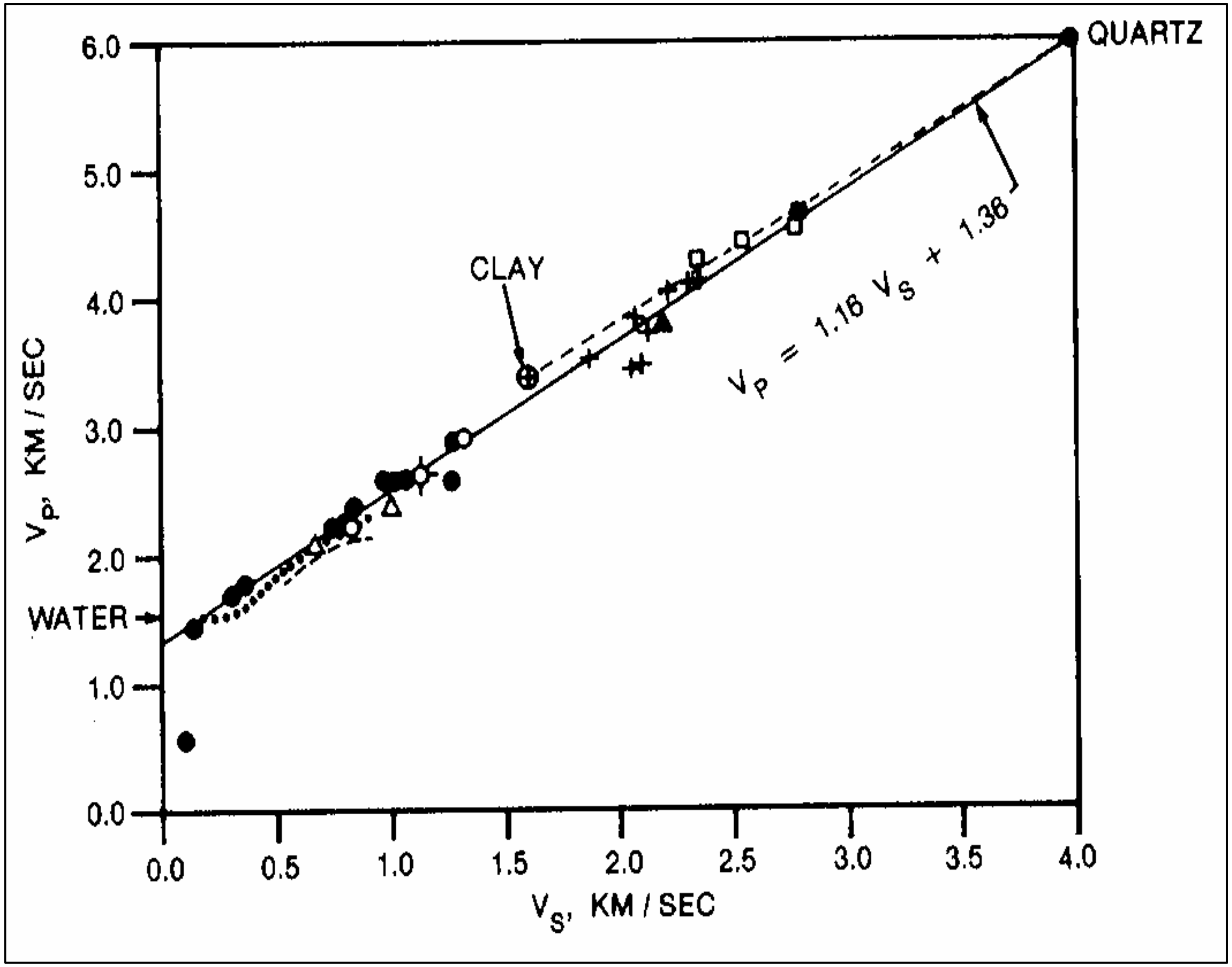
Target	Attribute	Error	Correlation
S-wave	P-wave	165.154755	0.730677
S-wave	Density	218.033646	0.433163
S-wave	Gamma Ray	226.306885	-0.353285

Regression statistics for the crossplots of all the well logs. Notice that P-wave velocity correlates best, followed by density, and then Gamma Ray.

The Arco mudrock line

The *mudrock line* is a linear relationship between V_P and V_S derived by Castagna et al (1985). The figure from their paper is on the right, and the equation is below:

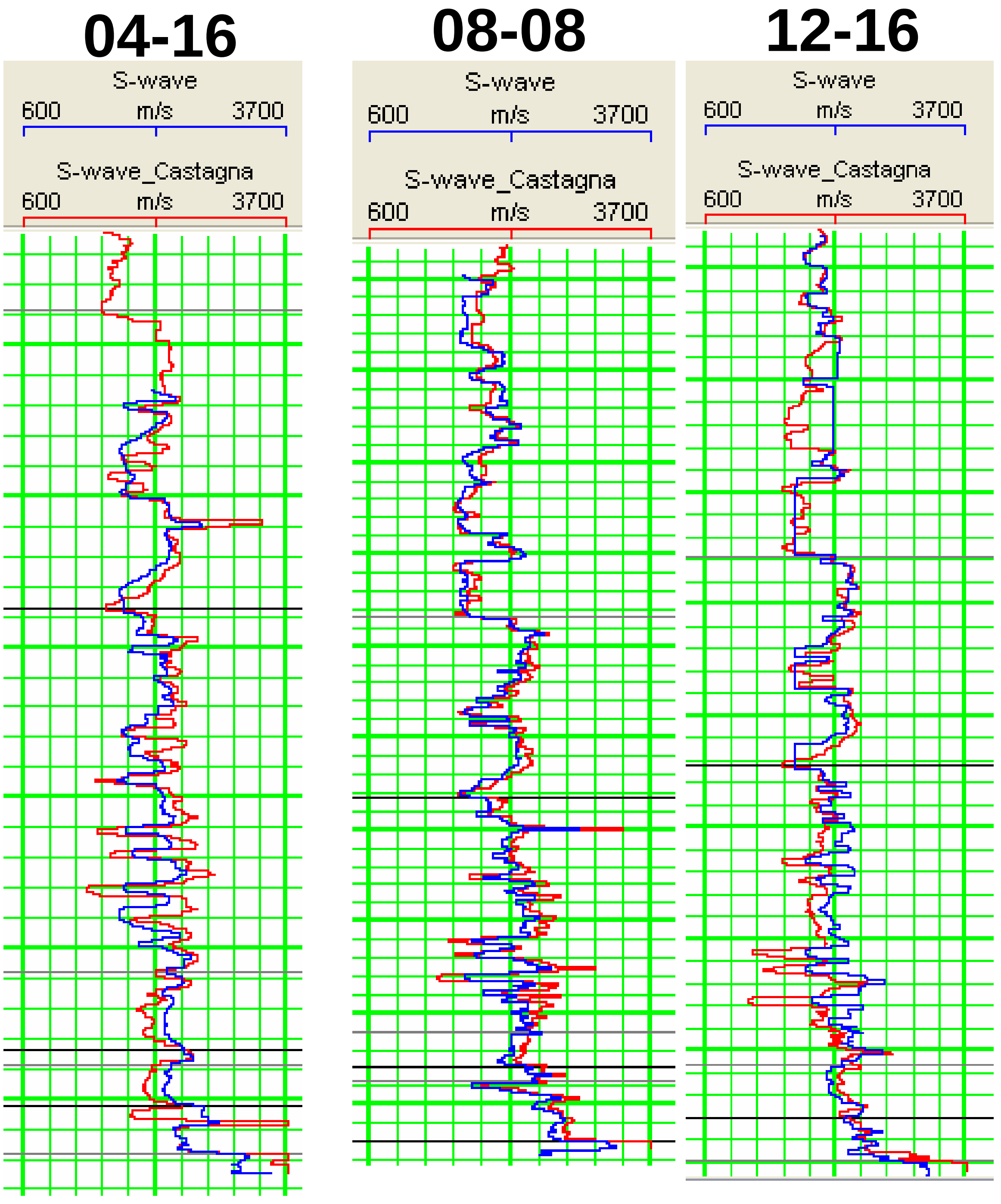
V_P=1.16V_S + 1360 m/s



ARCO's original mudrock derivation
(Castagna et al, Geophysics, 1985)

The Arco mudrock line

This plot shows the application of the ARCO mudrock line to the three wells shown earlier, where the blue curve is the original S-wave velocity log, and the red curve is the derived S-wave velocity curve. The fit is quite reasonable, but could be improved.



The generalized mudrock line

The *generalized mudrock line* can be written:

$$V_S = a + bV_P,$$

where the coefficients are derived from our local wells. The average coefficients derived for the three wells just shown are:

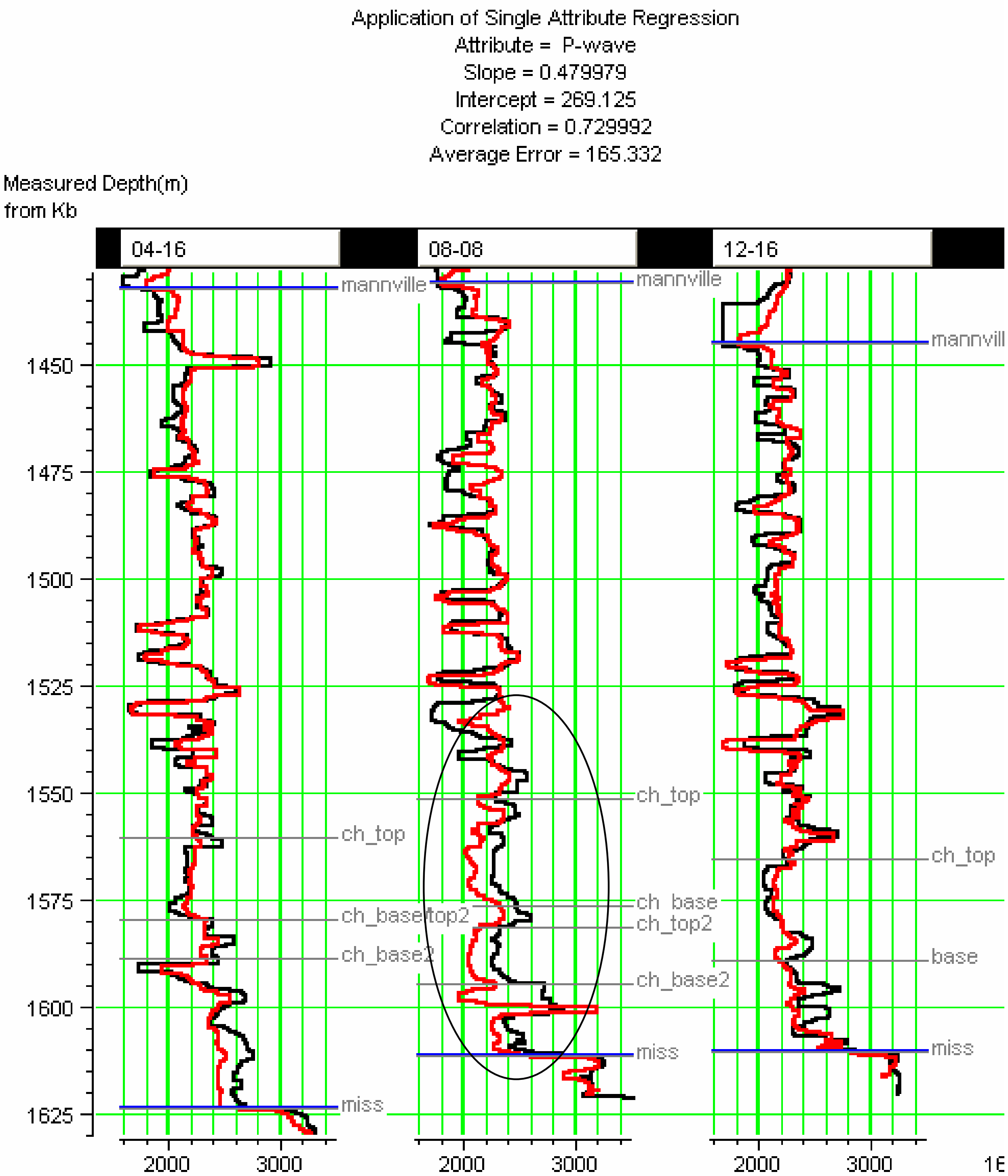
$$V_S = 269.125 + 0.480V_P$$

The application of this equation is shown in the next figure.

This plot shows the application of a average regression equation between Vp and Vs for all three wells. The black lines show the original logs and the red lines show the computed logs. Note that:

Corr Coeff = 0.73

RMS Error = 165



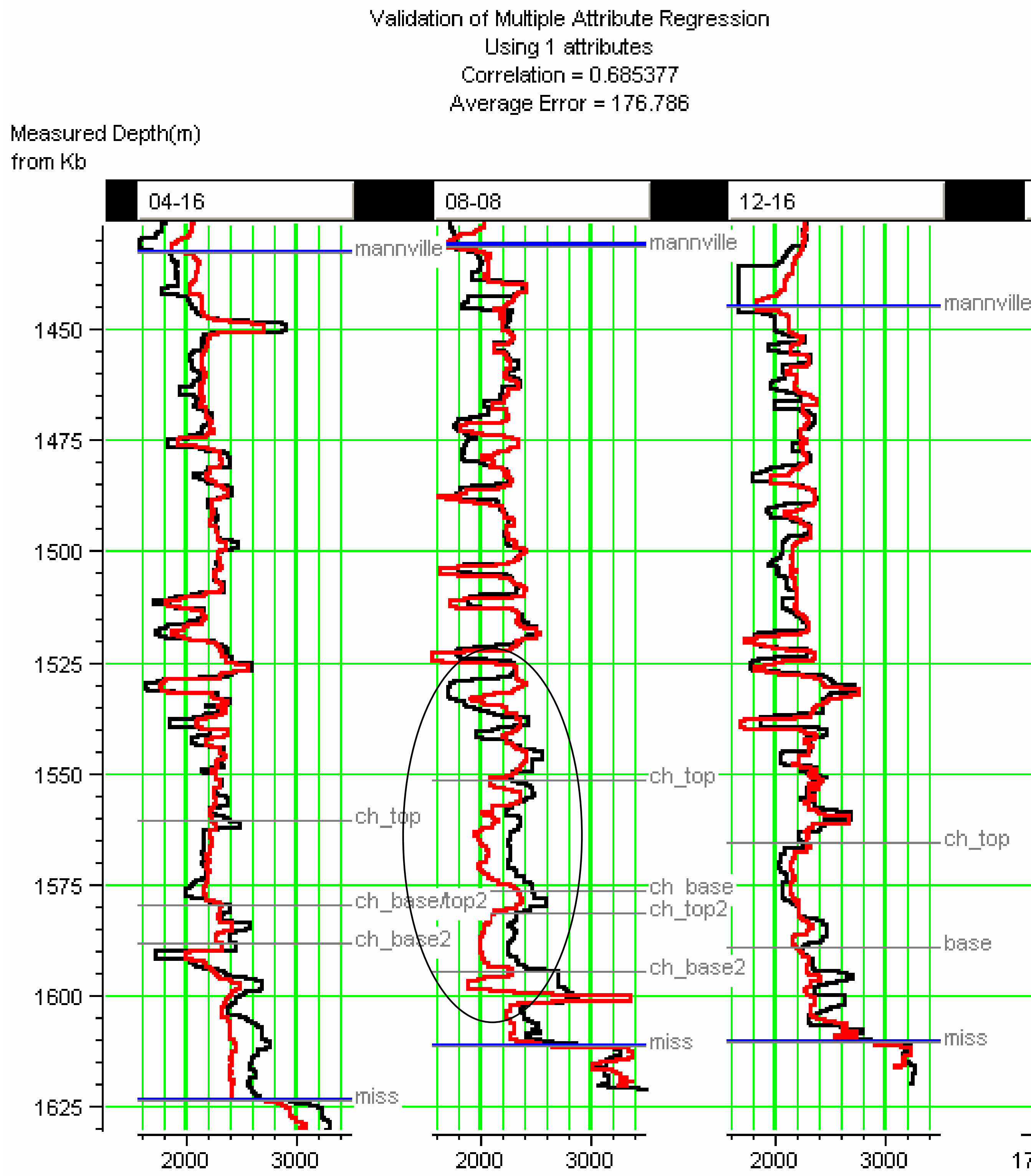
Validation of the mudrock line

- In the previous slide, the coefficients were derived from all three wells and then applied to all three wells.
- To test the validity of the mudrock line, we may use the cross-validation approach, in which the regression coefficients are derived from two of the wells, and then applied to the third.
- This is essentially a “blind test” of the well for which the prediction is made.
- The next slide shows the validation curves.

This plot shows the validation plots of the Vs curve for the three wells shown earlier. The black lines show the original logs and the red lines show the computed logs. We now find that:

Corr Coeff = 0.68

RMS Error = 177



Multilinear Regression

We will now use a *multilinear regression* approach to perform a multilinear regression of the form:

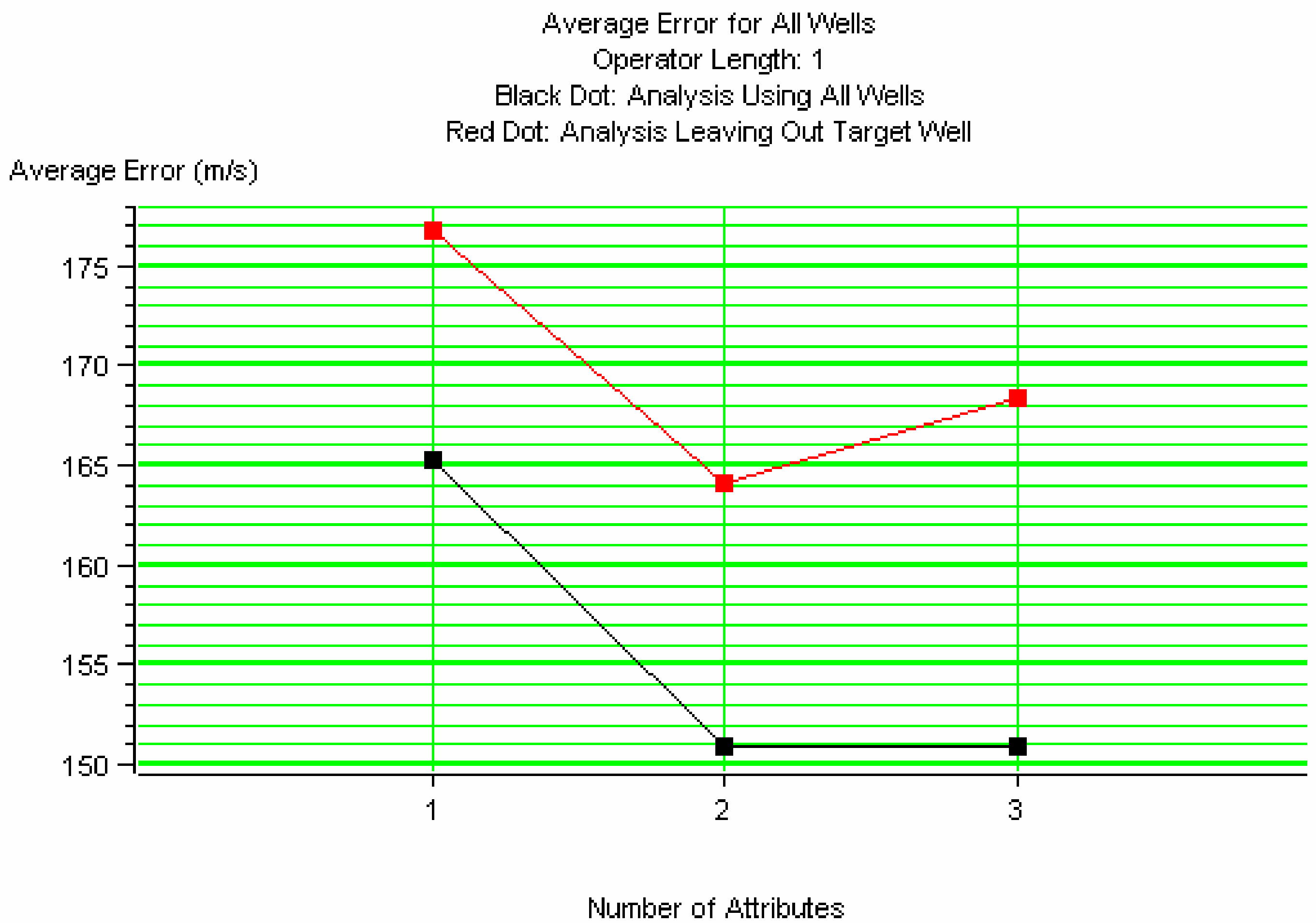
$$V_S = c_0 + c_1 L_1 + \ldots + c_N L_N,$$

where the $\boldsymbol{c_i}$ values are the weights and the $\boldsymbol{L_i}$ terms are the available logs. In our case, the P-wave velocity, density, and gamma ray logs are available for use.

The optimum attributes are found using a technique called ***step-wise regression***, and the valid attributes are found by ***cross-validation***. The next figure shows the result.

Multilinear Regression

Linear multivariate regression fit using all the well logs. P-wave velocity fits best, followed by Gamma Ray, and then Density. The validation curve (in red) shows that the density values actually increase the error.



	Target	Final Attribute	Training Error	Validation Error
1	S-wave	P-wave	165.332158	176.785774
2	S-wave	Gamma Ray	150.936775	164.085386
3	S-wave	Density	150.927284	168.372343

Multilinear Regression

The best multilinear regression equation is found to be:

$$V_S = 656 + 0.46 V_P - 3.5\,\gamma$$

where γ indicates the gamma ray log.

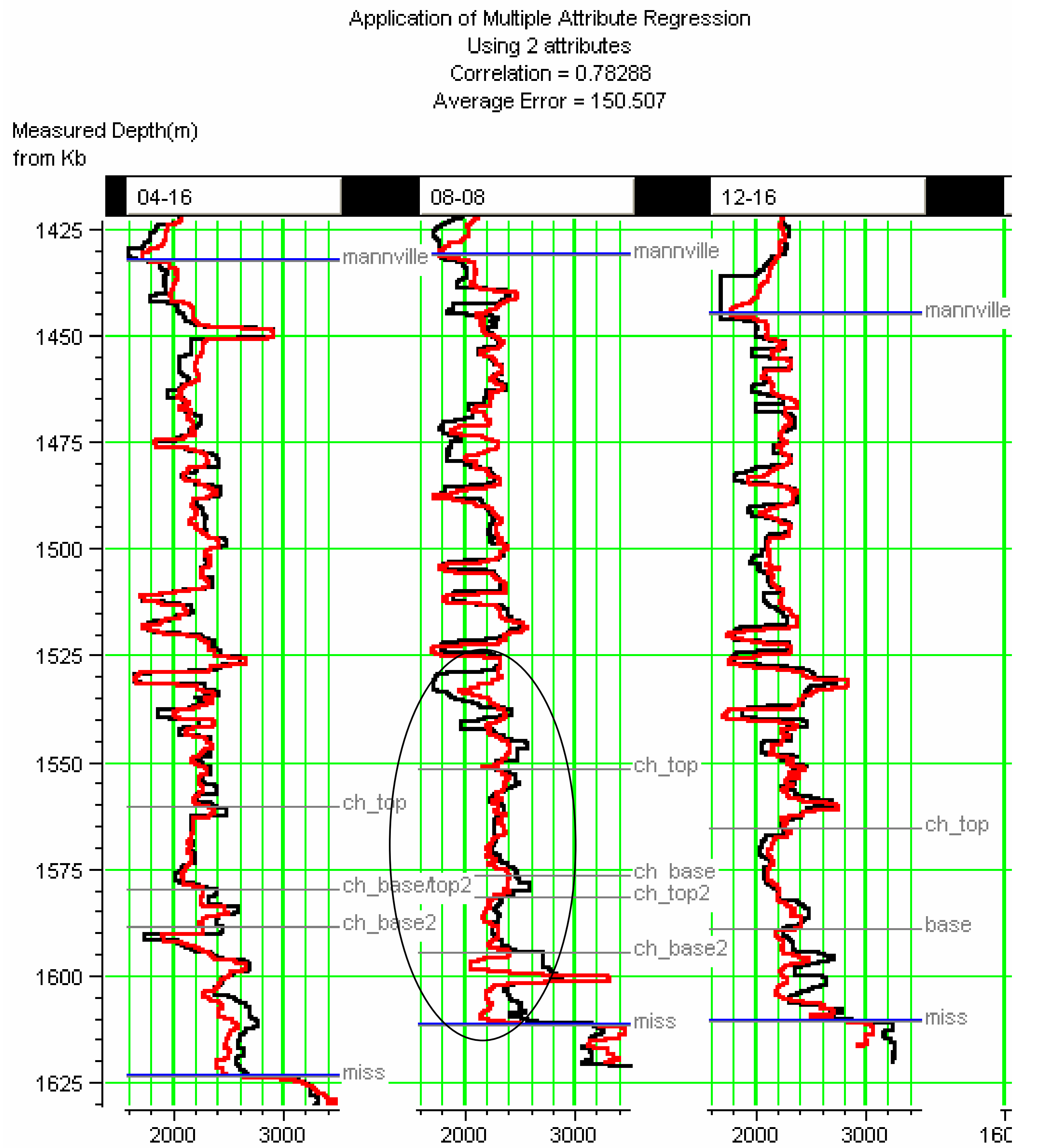
A modified approach is to apply nonlinear transforms such as inverse, square root, etc, to the logs before performing multilinear regression. This leads to the equation:

$$V_S = 893 + 0.46 V_P - 60.4\sqrt{\gamma}$$

This plot shows the application of the average regression equation of *Vs* against *Vp* and square root of γ for all three wells. The black lines show the original logs and the red lines show the computed logs. Note that:

Corr Coeff = 0.78

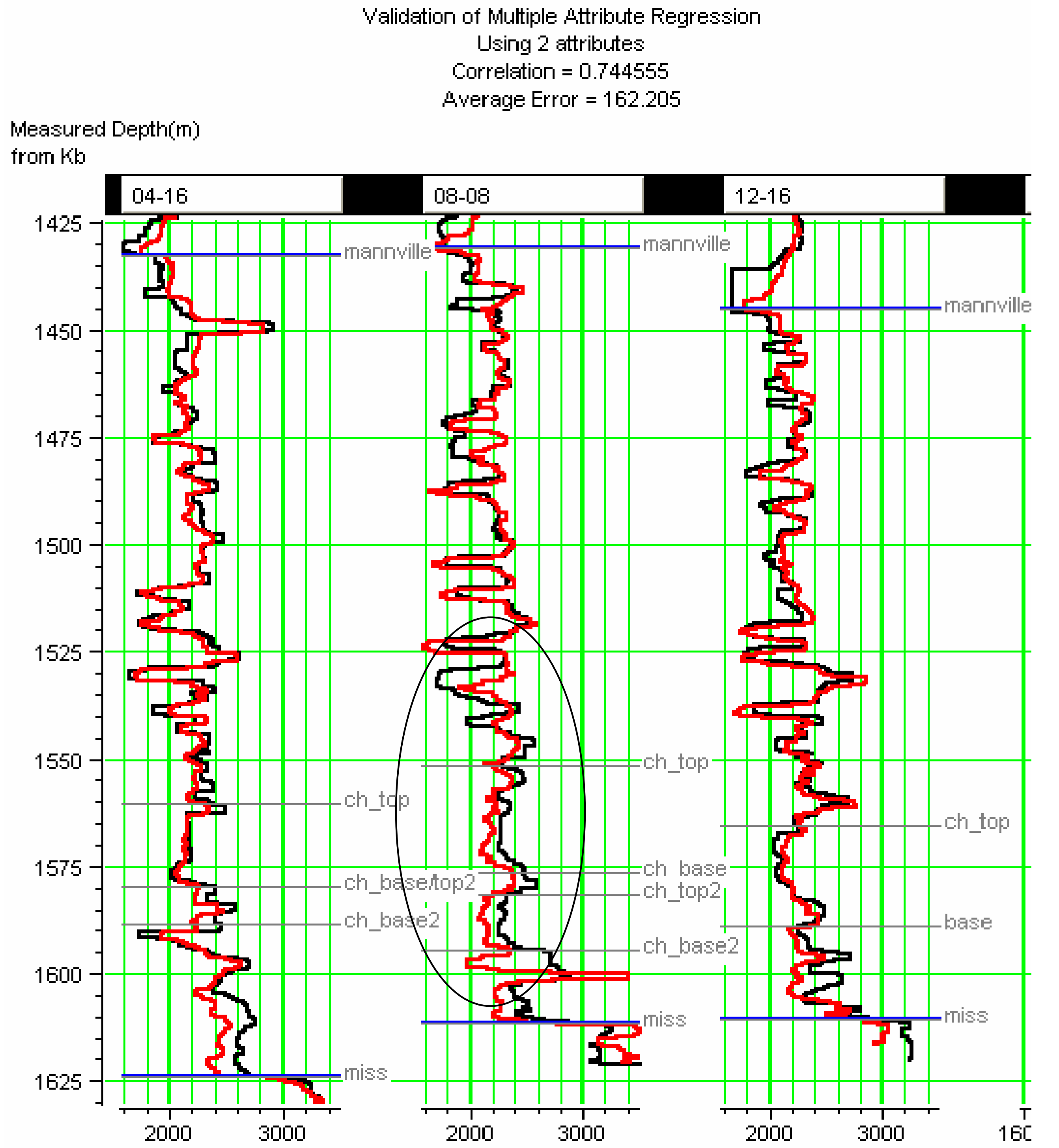
RMS Error = 151



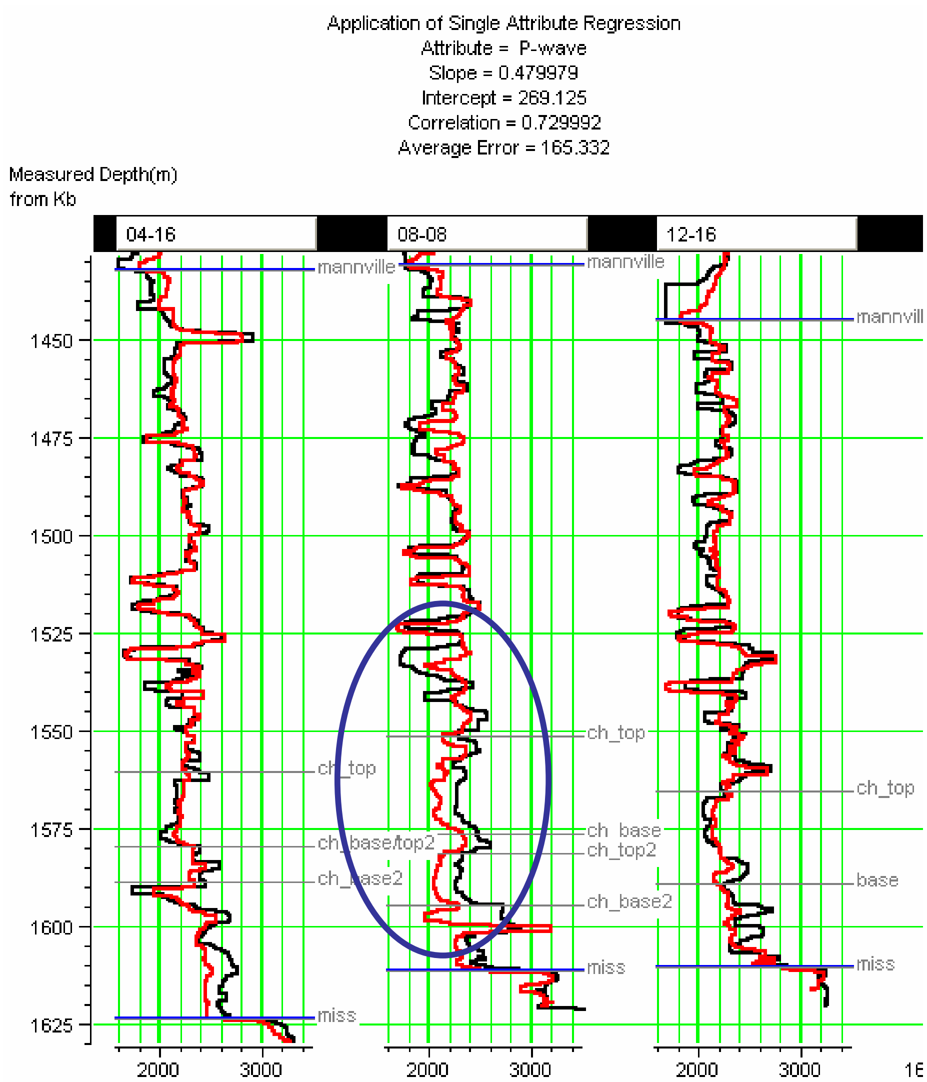
This plot shows the validation plots of the *Vs* curve for the three wells shown earlier. The black lines show the original logs and the red lines show the computed logs. We now find that:

Corr Coeff = 0.75

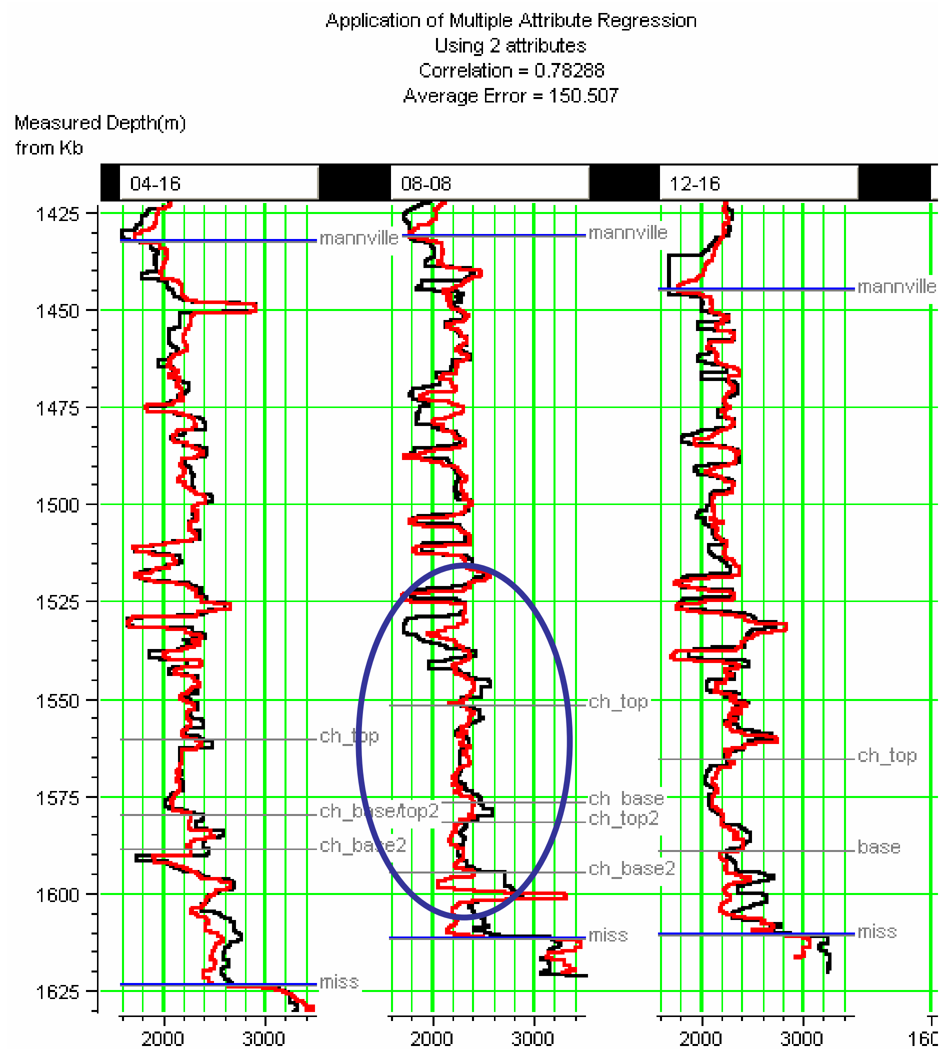
RMS Error = 162



Full training results

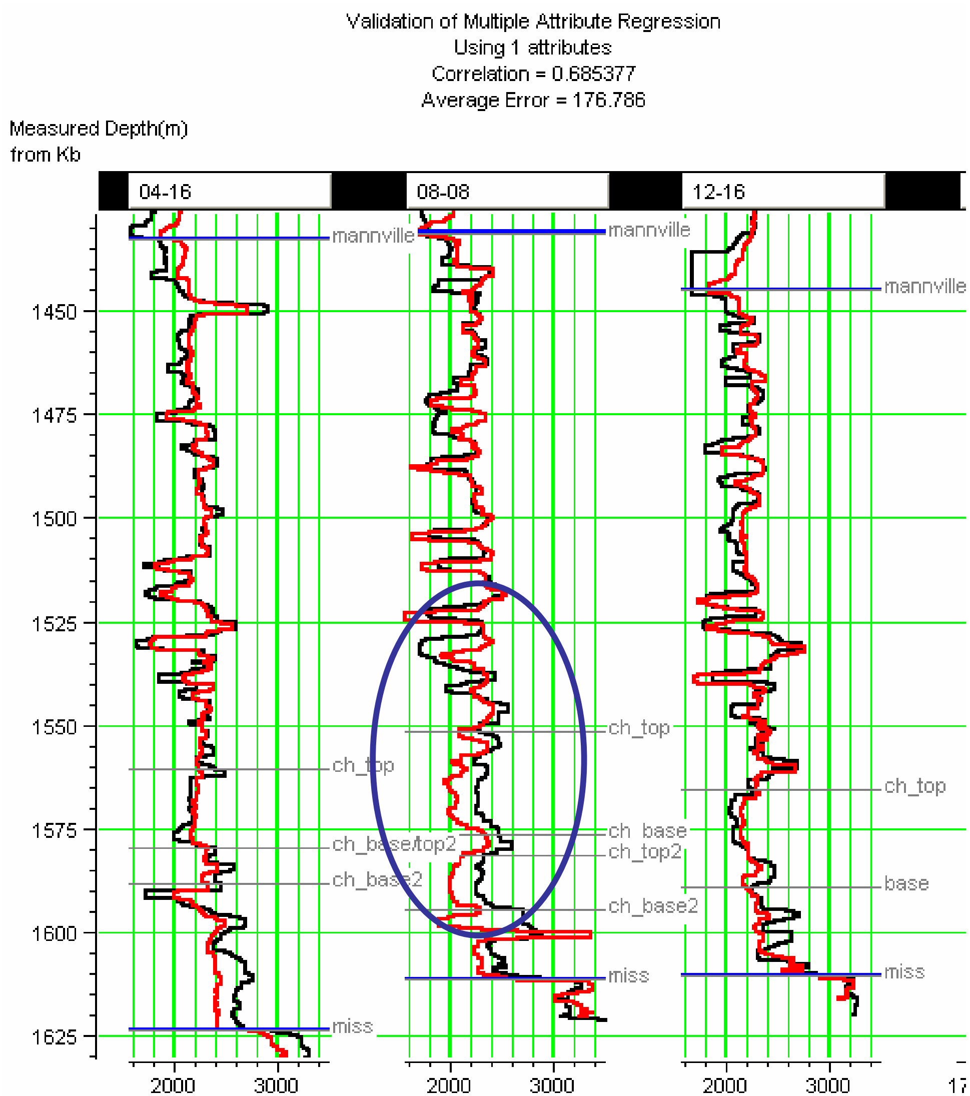


(a) The application of Vs vs Vp, where **Corr Coeff = 0.73** and **RMS Error = 165**.

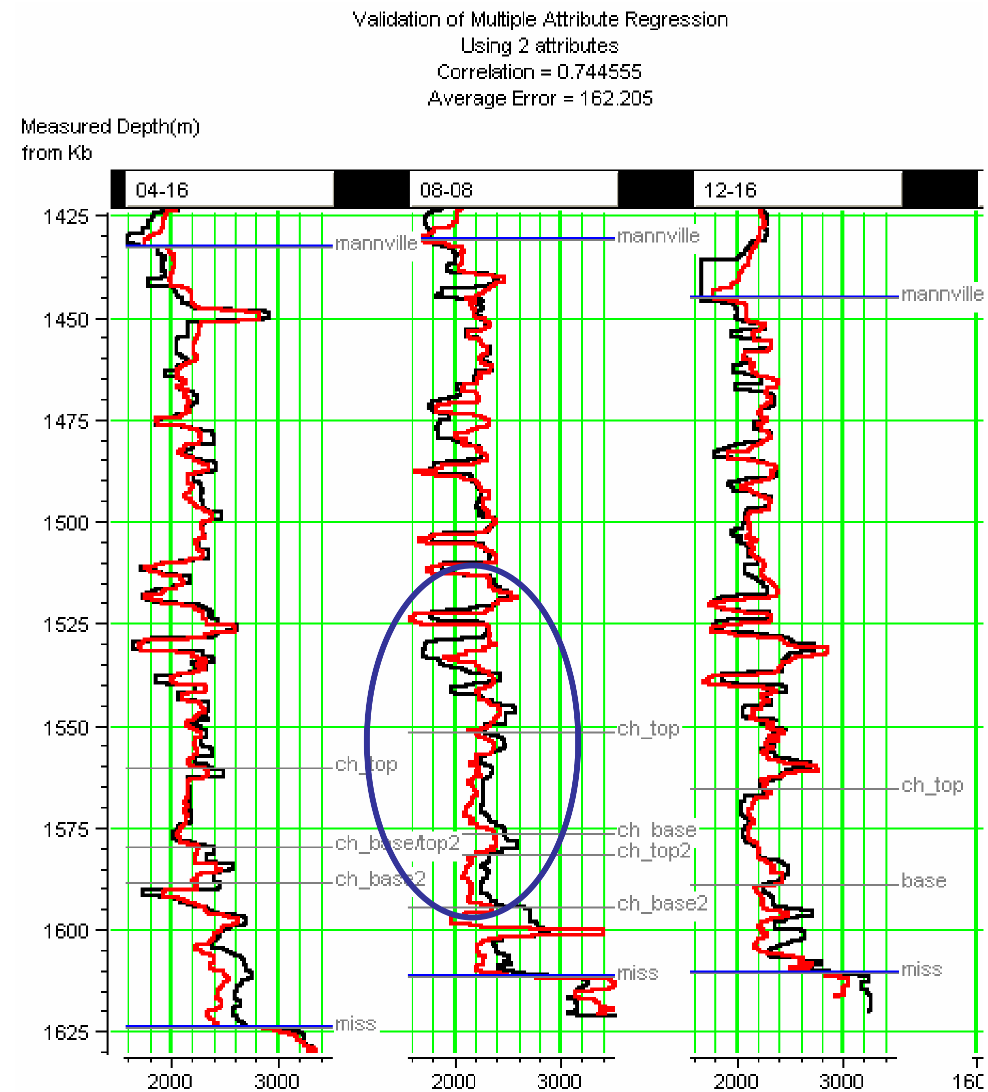


(b) The application of Vs vs Vp and γ, where **Corr Coeff = 0.78** and RMS **Error = 151**.

Validation results



(a) The validation of Vs vs Vp, where **Corr Coeff = 0.68** and **RMS Error = 177**. Note comparison.

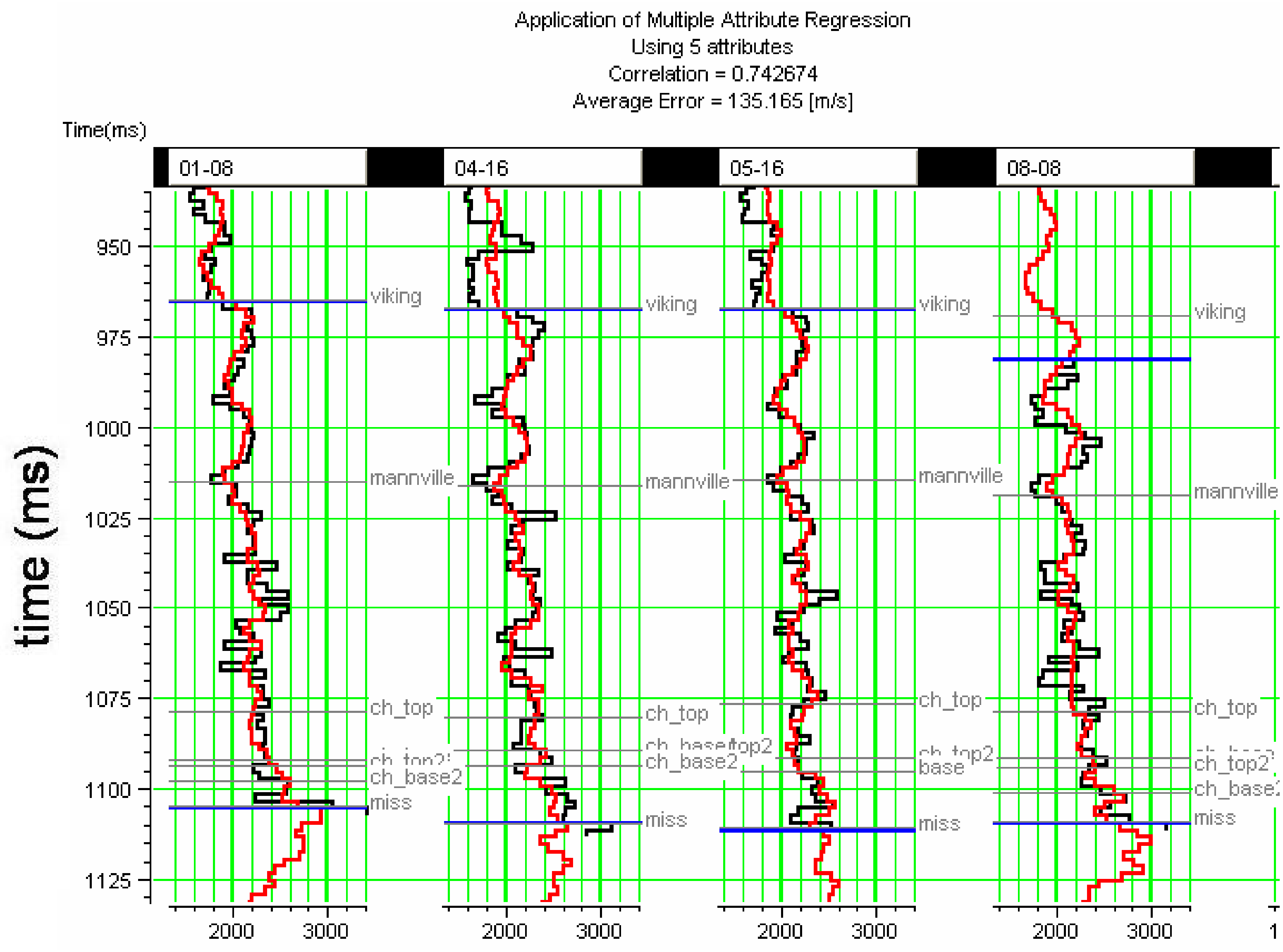


(b) The validation of Vs vs Vp and γ, where **Corr Coeff = 0.75** and RMS **Error = 162**. Note comparison.

Predicting an S-wave volume

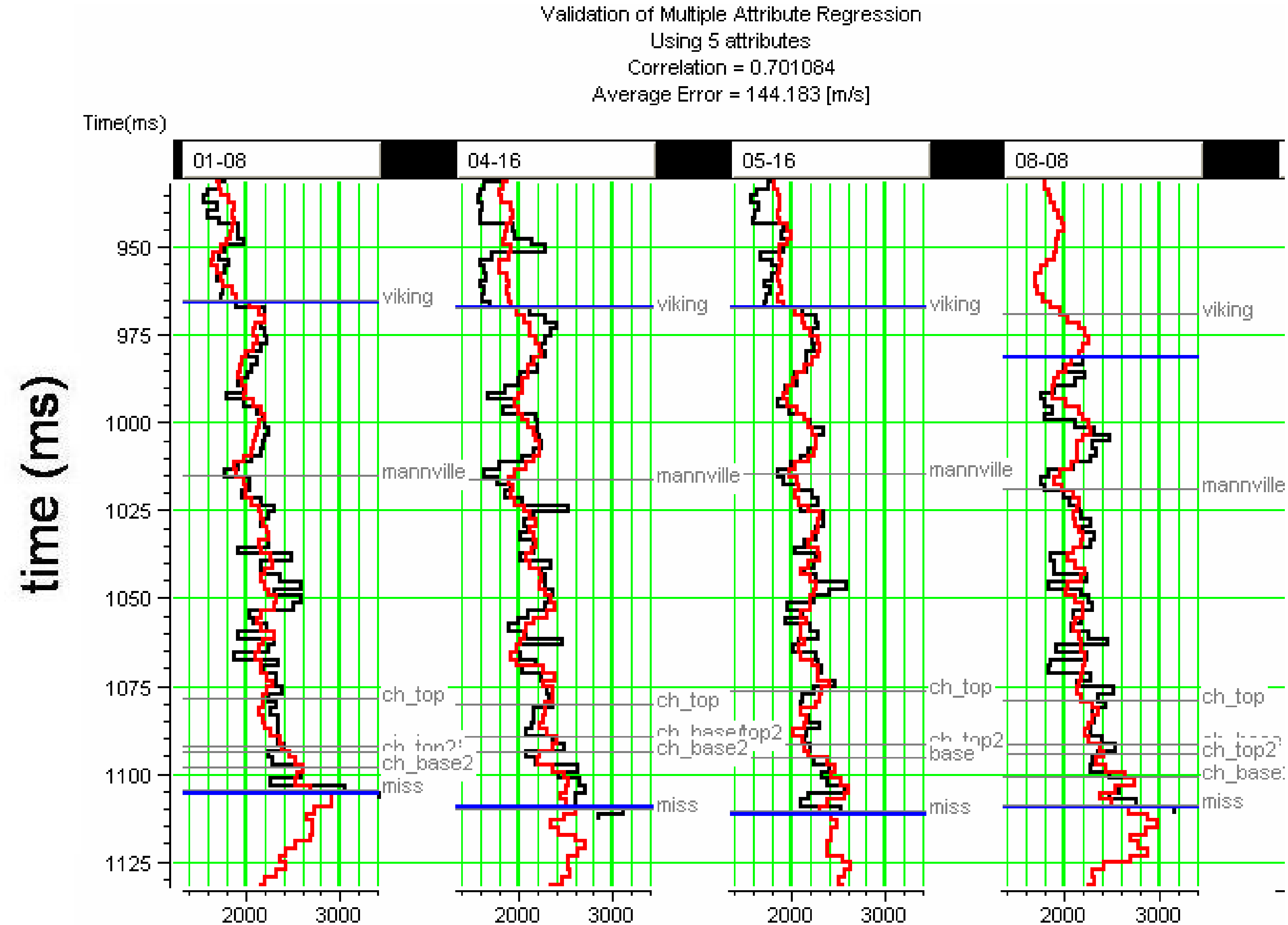
- Once we have found the new relationship using multiattribute analysis, we can apply it to the other six wells in our database, giving us S-wave velocity log curves in all nine wells.
- The nine wells can then be use as the basis for S-wave velocity inversion of a 3D R_S volume.
- The R_S volume can be derived using AVO analysis with the Fatti equation.
- The inversion is done using a model-based inversion approach.

Predicting an S-wave volume



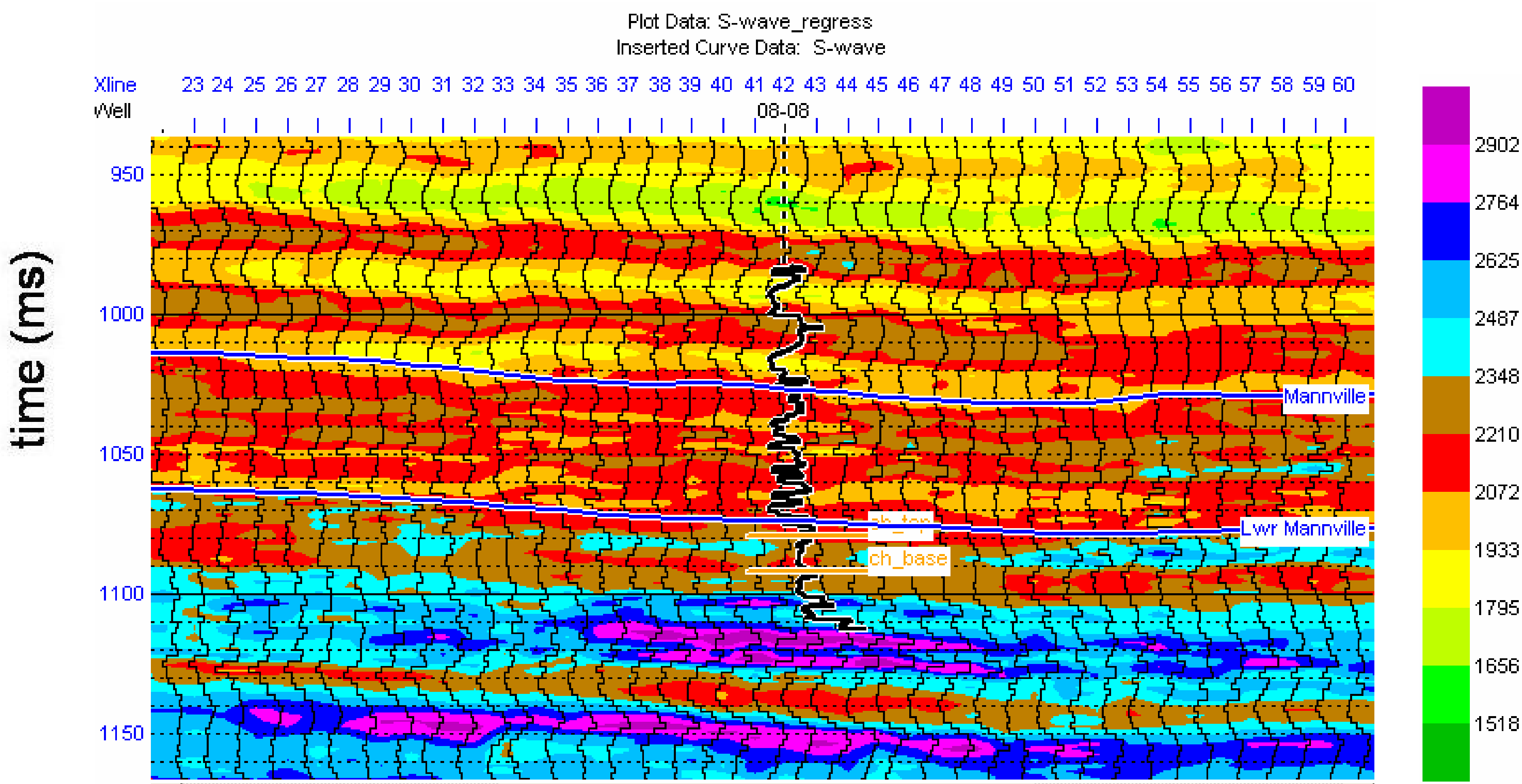
Here are the predicted curves for four of the wells using a set of seismic attributes.

Predicting an S-wave volume



Here are the validated curves for four of the wells using a set of seismic attributes.

Predicting an S-wave volume



Here are the predicted S-wave velocity values at the over a seismic line that is tied by well 08-08.

Conclusions

- In this talk, we used multilinear regression to predict S-wave velocity logs from combinations of other logs.
- This resulted in the derivation of a new statistical relationship for the prediction of S-wave velocity logs.
- This new relationship was compared to the ARCO mudrock line.
- This new equation was better able to distinguish between different lithologic units such as sands and shales.
- However, our conclusion is that a local fit using should be done rather than use a pre-existing regression equation.

Acknowledgements

- We wish to thank our colleagues at both CREWES and at Hampson-Russell Software for their input to this study.
- We also wish to thank the sponsors of the CREWES consortium.